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The impact of effective stress and gas slippage on coal permeability under cyclic loading

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ABSTRACT

The determination of the effective stress coefficient of porous media (such as coal) remains a controversial issue. The purpose of this paper is to determine the effective stress coefficient of coal during gas penetration and to investigate the impact of effective stress and gas slippage on coal permeability under cyclic loading conditions. Analyzing the evolution law of coal anisotropic permeability with effective stress allows the deformation characteristics of the coal's internal structure, such as cleat or bedding, to be studied. The effective stress coefficient of long flame coal is obtained through modified permeability models based on experimental data. Test results show that the slippage effect significantly influences the permeability of coal samples, specifically in the range of low pore gas pressure, and that the effect of gas slippage is larger than that of effective stress. Permeability decreases gradually when effective stress increases, but it increases during unloading, and ascending and descending curves show significant irreversibility of permeability. Moreover, *PLR* (permeability loss rate) and *IPLR* (irreversible permeability loss rate) results indicate that the influence of effective stress on permeability perpendicular to bedding is greater than that of permeability parallel to bedding and that the ability of the cleat to resist deformation induced by effective stress is weaker than that of bedding. Under identical pressure conditions, the cleat shows more vulnerability and produces larger plastic deformation.

1. Introduction

Coal permeability is controlled by fractures, which include size, spacing, connectedness, aperture and degree of mineral infill, and patterns of orientation (Laubach et al., 1998). It is connected to coal type and rank (Clarkson and Bustin, 1997), sorption characteristics (Liu et al., 2011; Mazumder et al., 2012), temperature and other factors. To better study permeability, an increasing number of scholars have begun to derive and improve the permeability model first proposed by Gray, 1987 (Sawyer et al., 1987, 1990; Seidle and Huitt, 1995; Levine, 1996; Palmer and Mansoori, 1996, 1998; Shi and Durucan, 2004a, 2005; Cui and Bustin 2005, 2007; Wang et al., 2012). Most of these models were derived to simulate field conditions and assume matrix-block geometry described as a bundle of vertical matchsticks under a uniaxial stress regime (Palmer and Mansoori, 1998). However, these permeability models are not suitable for laboratory conditions under which the confining pressure is generally held constant, permeability evolution under various loading conditions, hydrostatic stress or deviatoric stress can be studied using experimental equipment; in addition, radial expansion resulting from gas adsorption is allowed during gas penetration. For this reason, some researchers proposed new permeability models for laboratory triaxial permeability tests (Wang et al., 2009). In addition, some models are conditions (stresses)-specific such as PM model while others are valid for any stress conditions such as Zhang et al. (2008). In this paper, in order to obtain the effective stress coefficient, two permeability models that are suitable for laboratory test conditions were used— the McKee et al. model (1988) and the Robertson et al. model (2006).

Coal is a weak rock with cleat aperture, and thus, permeability is sensitive to effective stress (Pan and Connell, 2012). As effective stress increases, permeability decreases exponentially; this relationship is supported by extensive laboratory studies (Seidle et al.,

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1992; Somerton et al., 1975). Under the action of effective stress, the flow channels within micro-fractures become narrower, and some may close completely; consequently, permeability decreases dramatically at high effective stress levels (Huy et al., 2010). The importance of the effective stress coefficient has been widely realized for both primary gas production of coal media and predictions of gas outbursts. In most of the previous permeability modeling work, the effective stress coefficient for coal is often set at unity, though laboratory measurements have shown that the effective stress coefficient is less than unity (Chen et al., 2011; Zhao et al., 2003). Walsh (1981) showed that $\beta = 0.9$ for a rock mass containing a polished joint, and Kranzz et al. (1979) defined $\beta = 0.56$ for rock containing a tensile joint. Assuming effective stress coefficient to be unity will lead to overestimating the effective stress change during pressure drawdown, thus it may lead to overestimation of permeability change (Pan and Connell, 2012). In this paper, the effective stress coefficient β is not unity and determined from laboratory test results.

The gas slippage effect was first proposed by Klinkenberg in 1941 and describes the phenomenon of gas penetrating channels of porous media such that the gas molecules close to the cell walls show a non-zero flow rate. The gas slippage effect has a great impact on penetration, especially in low permeability media. The existence of slippage is good for increasing reservoir permeability, which makes exploitation of large-scale low permeability coal bed methane media possible, and thus research into the gas slippage effect on low permeability medium. Through, the slippage effect also has its restriction. It has been found that the gas slippage effect diminishes with increasing of gas pressure because at high pressures (e.g., >2 MPa), the mean free path of the gas molecules (diameter of approximately 0.98 Å) is far less than the aperture of the coal cleats (3–40 μm) (Laubach et al., 1998). However, permeability models without considering the gas slippage effect can't accurately match the test results, especially for low permeability media.

In this paper, anisotropic permeability behaviors for low-rank coal samples (long flame coal), namely, parallel and perpendicular to coal bedding have been studied by N_2 under cyclic loading conditions. The gas slippage effect and the effective stress coefficient have been considered to describe the anisotropic permeability behavior of low-rank coal. The evolution law of coal anisotropic permeability with effective stress has been systematically studied.

2. Laboratory permeability tests

2.1. Sample preparation and permeability test procedure

The long flame coal from the Hunchun coalfield in Jilin province of China is shown in Fig. 1. With developed multi-minable coal seams, the regional structural characteristics of Hunchun coalfield are relatively simple and clear. The largest proportion of coal in the 26th coal seam is semi-bright coal, which is followed by the semi-dark type. The average bulk density is 1340 kg/m^3. The majority of macerals is vitrinite, at 78.59%, while the proportions of inertinite and exinite are 4.21% and 1.25%, respectively; the maximum vitrinite reflectance is 0.567%. The seam's existing occurrence depth increases with distance, with the vitrinite reflectance rising 0.05% every 100 m. The main indicators obtained in the coal quality test are summarized in Table 1.

All samples were trimmed to a dimension of Φ50 × 100 mm. To study the anisotropy of coal permeability, two types of coal samples were prepared. Sample M4 was parallel to the bedding, while samples M1, M2 and M3 were perpendicular to the bedding; the schematic diagram of sample preparation is shown in Fig. 2.

A low-permeability rock permeability test system (Fig. 3) has been developed by Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. The inlet gas pressure control valve was used to control the upper surface pressure of the specimen, and the outlet was connected to the outside. A soap bubble flow meter was used to measure gas flow. After forming steady-state flow between the upper and lower surfaces of the specimen under differential pressure, the gas penetration rate, i.e., the gas flow per unit time was measured at the outlet end. The average pore pressure is determined by the inlet and outlet gas pressure, i.e., $p = (p_{in} + p_{out})/2$, where p_{in} and p_{out} represent the inlet pressure and outlet pressure respectively. The laboratory room temperature is controlled at 27 °C.

Permeability of coal samples under different gas pressures were tested by N_2 under cyclic loading conditions. The cyclic loading process has two sections, which comprise cyclic hydrostatic stress and cyclic deviatoric stress (confining pressure was maintained at 8 MPa and 14 MPa, respectively). Cyclic loading paths are shown in Fig. 4.

2.2. Test results

Fig. 5 shows the coal samples' permeability test results under different hydrostatic stresses. Generally, permeability parallel to the bedding is larger than perpendicular to the bedding (Gash et al., 1992; Wang et al., 2014). Fig. 5 shows that the magnitude of vertical permeability tested by samples M1-M3 is 1-2 orders of magnitude smaller than the horizontal permeability tested by sample M4. Apparent permeability declines exponentially with increasing pore pressure, this result was also obtained by many other researchers (Chen et al., 2011; Jasinge et al., 2011; Mavor and Gunter, 2006). With increasing gas pressure, permeability parallel to bedding decreases more significantly. A significant decline is shown prior to a pore pressure 0.65 MPa, and this gradually stabilizes. The permeability loss rate when penetrative pore pressure increases from 0.25 MPa to 0.65 MPa is calculated according to Eq. (1).

$$PLR = \frac{\Delta K}{K_0} \tag{1}$$

Where ΔK is permeability decrement and K_0 is the initial permeability when pore pressure is 0.25 MPa. By this calculation, the *PLR* of samples M1, M2, M3 and M4 are 0.35, 0.31, 0.30 and 0.44, respectively; horizontal permeability was significantly greater than vertical permeability. The anisotropy of *PLR* could reflect the stress sensitivity of internal coal structures, such as cleats or beddings, and is affected by the gas slippage effect or effective stress. This, combined with, the mechanical characteristics of internal coal structures is analyzed in detail in chapters 4 and 5. Fig. 5 (e) and (f) show coal permeability evolution under cyclic hydrostatic stress, while Figs. 6 and 7 show the same under cyclic deviatoric stress (maintaining confining pressures of 8 MPa and 14 MPa, respectively). Permeability declines when hydrostatic stress or axial stress increases and rebounds during the unloading process. The slope of the loading curve is significantly larger than that when unloading, which indicates that irreversible plastic deformation is generated at each stress cycle.

3. Determination of the effective stress coefficient

Effective stress for porous medium is expressed as

$$\sigma = \sigma_t - \beta P \tag{2}$$

Where σ is effective stress; σ_t is total stress; P is the average pore pressure; and β is effective stress coefficient, where $0 \le \beta \le 1$. In